Ultracold neutrons production and detection

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ESIPAP lecture 2015
Outline

1 Neutron optics, ultracold neutrons

2 Fundamental physics with UCNs
   Neutron lifetime
   Electric dipole moment
   Gravity with neutrons

3 Neutron detection

4 UCN sources
Neutron spectrum

Fission ~ 2 MeV

Resonant capture ~ 10 eV

Thermal neutrons: $kT = 25$ meV @ $T = 300$ K

Fermi potentials ~ 100 neV

De Broglie wavelength
\[ \lambda = \frac{2\pi \hbar}{\sqrt{2mE}} \]

$\lambda < 0.1$ nm

“PARTICLE”

$\lambda > 0.1$ nm

“WAVE”
Mirror effect (absent)
Mirror effect (present)
Particles and waves
Neutron interaction with a single nucleus

Potential scattering described by non-relativistic quantum scattering theory. For nonrelativistic neutrons, nuclei look point-like ($kR_{\text{nucl}} \ll 1$):

- Isotropic scattering
- Energy-independent

Neutron wave function corresponding to the scattering process:

\[
\psi(r) = e^{ikx} - a \frac{e^{ikr}}{r} \quad \text{(center of mass frame)}
\]

\[
\psi(r) = e^{ikx} - b \frac{e^{ikr}}{r} \quad \text{(lab frame)}
\]

\[
b = \frac{A + 1}{A} a
\]

Scattering X-section:

\[
\sigma = 4\pi b^2
\]
Measured neutron scattering lengths

For a catalog, see http://www.ncnr.nist.gov/resources/n-lengths

Surprisingly, almost all nuclei have $b > 0$. 
Neutron interaction with a collection of nuclei

Incident neutron with energy \( E = (\hbar k)^2 / 2m \)

Self consistency of the wave function
\[
\psi(\vec{r}) = e^{i k \vec{x}} - \sum_j \psi(\vec{R}_j) b \frac{e^{i k |\vec{r} - \vec{R}_j|}}{|\vec{r} - \vec{R}_j|}
\]

Using the relation
\[
(\Delta + k^2) \frac{e^{i k |\vec{r} - \vec{R}_j|}}{|\vec{r} - \vec{R}_j|} = -4\pi \delta(\vec{r} - \vec{R}_j)
\]

We find the wave equation
\[
(\Delta + k^2)\psi(\vec{r}) = 4\pi b \sum_j \delta(\vec{r} - \vec{R}_j) \psi(\vec{r}) \\
\approx 4\pi b n \psi(\vec{r})
\]

\( n \) is the nuclear density of the medium
Defining the Fermi potential of a medium

\[ V = \frac{2\pi \hbar^2}{m} b n \]

The wave equation is a Schrödinger equation with the potential \( V \)

\[ \left( -\frac{\hbar^2 \Delta}{2m} + V \right) \psi(\vec{r}) = E \psi(\vec{r}) \]

For cold neutrons, bulk matter is characterized by its Fermi potential. We expect wave phenomena (refraction, reflection, tunnel transmission..).

### Examples

<table>
<thead>
<tr>
<th>Material</th>
<th>b [fm]</th>
<th>n ([\text{cm}^{-3}])</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>3.45</td>
<td>6.02 x 10^{22}</td>
<td>54 neV</td>
</tr>
<tr>
<td>Iron ((^{56})Fe)</td>
<td>9.45</td>
<td>8.49 x 10^{22}</td>
<td>209 neV</td>
</tr>
<tr>
<td>Nickel ((^{58})Ni)</td>
<td>14.4</td>
<td>9.13 x 10^{22}</td>
<td>340 neV</td>
</tr>
<tr>
<td>Natural Nickel</td>
<td></td>
<td>9.13 x 10^{22}</td>
<td>245 neV</td>
</tr>
</tbody>
</table>

For heterogeneous materials (atomically like water, or isotopically like natural nickel), one sums the Fermi potentials of each nuclear specie:

\[ V = \frac{(2\pi \hbar^2)}{m} \sum b_i n_i \]
Total reflection of neutrons

Solid matter characterized by the Fermi potential $V_F$

Condition for total reflection of neutrons
Fermi, Zinn (1946)

$$E \sin^2 \theta < V_F$$

Example:
thermal neutrons ($E=25$ meV) are guided through a Nickel guide ($V=245$ neV) provided

$$\theta < 0.2 \text{ deg}$$
Application: transporting neutrons 100 m…

Institut Laue Langevin, Grenoble High Flux Reactor

Guide Hall
Neutron distribution channels at ILL
Ultracold neutrons (UCN)

Neutrons with energy $< 100$ neV, or velocity $< 5$ m/s are reflected by material walls.

We can store them in bottles!
UCN plumbing

UCNs are guided through evacuated stainless steel pipes (about 10 cm diameter) and bends.

Losses are generally percents/meter
UCNs and gravity

UCNs feel gravity

\[ mg \times (1 \text{ m}) = 100 \text{ neV} \]

Very important for UCN techniques

- We accelerate UCNs to detect them (otherwise they would bounce off the detector window).
- Some UCN traps do not need a roof.
- Lifting an experiment by 50 cm can modify significantly the results!
UCNs and gravity

The U device

If you want to remove UCNs with energy $E < 80$ neV,
Just set $h = 80$ cm
UCNs and magnetic fields

Neutron magnetic moment

\[ \mu_n \times (1 \, \text{T}) = 60 \, \text{neV} \]

Magnetic fields act on the spin \( \frac{1}{2} \) neutron

\[ V = -\hat{\mu}_n \vec{B} \]

Input: unpolarized UCNs
Magnetized foil
Output: polarized UCNs
Summary

UCNs can be manipulated using

- The nuclear force (Fermi potentials ~ 100 neV)
- The gravitational force (1 m = 100 neV)
- Magnetic fields (1T = 60 neV)

They are used to study the fundamental interactions and symmetries

- Weak interaction (beta decay period 10 min)
- Electromagnetic properties of the neutron (EDM)
- Gravitational effects
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   - Electric dipole moment
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The neutron beta decay lifetime, why bother?

\[ n \rightarrow p + e^- + \bar{\nu}_e + 782 \text{ keV} \]

Free neutron lifetime
\[ \tau_n = 880.0(9) \text{ s} \]
[PDG 2013]

**Particle physics:**
extracting CKM matrix element \( V_{ud} \)

**Astrophysics and Neutrinos**
Calculating weak semi-leptonic processes like
\[
p + p \rightarrow d + e^+ + \nu_e
\]
\[
\bar{\nu}_\mu + p \rightarrow \mu^+ + n
\]

**Cosmology**
Predicting the yields of the BigBang Nucleosynthesis
Two complementary experimental methods

**Counting the dead neutrons: BEAM METHOD**

A detector records the decay products in a well defined part of a neutron beam. A neutron beam is indeed radioactive due to beta decay.

\[- \frac{dN}{dt} = \frac{N}{\tau_n} \]

**Counting the surviving neutrons: BOTTLE METHOD**

UCNs are stored in a bottle, the number of neutrons remaining in the bottle after a certain storage time $t$ is measured.

\[ N(t) = N(0) e^{-t/\tau_n} \]
Early beam method: counting the beta electrons

Christensen et al (1972)

Protons produced almost at rest (endpoint energy = 800 eV) are accumulated in a Penning trap.
Principle of a bottle UCN measurement

Typical sequence

1. Switch moved to FILL position, Valve OPEN for 20 s
2. Close Valve, Switch moved to EMPTY position
3. Wait period $t$
4. OPEN Valve, count neutrons

Repeat the sequence with different $t$
Principle of a bottle UCN measurement

Example: measured storage curve in the 20 L chamber of the EDM experiment

Problem: UCN losses at wall reflection are not negligible.

\[
\frac{1}{\tau_{st}} = \frac{1}{\tau_n} + \frac{1}{\tau_{wall}}
\]
Estimating the wall losses

The probability for a UCN to be lost at a wall collision can be of the order of

\[ \mu \approx 10^{-4} \]

The mean free path between collisions is of the order of

\[ \lambda \approx 30 \text{ cm} \]

The frequency of wall collisions for a velocity of 3 m/s is of the order of

\[ f = \frac{v}{\lambda} \approx 10 \text{ Hz} \]

The partial lifetime due to wall losses is thus of the order of

\[ \tau_{wall} = \frac{1}{f \mu} \approx 1000 \text{ s} \]
Good to know: the Clausius law

When mechanical equilibrium is achieved (isotropic velocity distribution) the mean free path between wall collisions is

$$\lambda = \frac{4V}{S}$$

Consider a bottle with arbitrary shape, of volume V and surface S.

$$\lambda = \frac{2d}{3}$$

$$\lambda = \frac{dh}{d/2 + h}$$

$$\lambda = \frac{2abh}{ab + ah + bh}$$

Results valid without gravity!
More on wall losses (a complicated topic)

- The wall loss probability is energy-dependent
  \[ \mu(E) = 2\eta \left( \frac{V}{E} \arcsin \sqrt{\frac{E}{V}} - \sqrt{\frac{V}{E} - 1} \right) \]

- It depends on temperature (the colder the better)

- Losses can be calculated from absorption and inelastic scattering cross section data. But measured losses are generally higher, due to surface impurities (hydrogen, in particular)
Example: MAMBO I (ILL, 1989)

The trap geometry is varied, one extrapolates the storage time to infinite mean free path.
Current status on the neutron lifetime

The 2014 situation
There is a $3.8 \sigma$ discrepancy between the bottle method combination and the beam method combination.

To be continued...
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The neutron electric dipole moment

\[ H = -\vec{\mu}_n \cdot \vec{B} - \vec{d}_n \cdot \vec{E} = \hbar \nu_L / 2 \]

A non-zero EDM would violate

- The parity symmetry
- The time reversal symmetry, thus the CP symmetry (CPT theorem)

\[ \nu_L(\uparrow\uparrow) - \nu_L(\uparrow\downarrow) = -\frac{4d_n}{\hbar} E \]
Explaining the baryogenesis

Sakharov conditions
To explain the matter-antimatter asymmetry in the Universe

1 **Departure from thermal equilibrium**
   It happens during a phase transition in the early universe... Electroweak phase transition?

2 **Violation of B conservation**
   OK in the Standard Model

3 **CP violation**
   The Standard Model (KM) CP violation does not generate enough asymmetry. One needs CP violation beyond the SM. This new physics would also generate a non zero neutron EDM.
The Ramsey method

“Spin up” neutron...

Apply $\pi/2$ spin-flip pulse...

Free precession...

$T \sim 200$ s

Second $\pi/2$ spin-flip pulse

\[ \sigma d_n = \frac{\hbar}{2 \alpha E T \sqrt{N}} \]

- polarization
- electric field
- precession time
- counts
Typical nEDM experiment
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Bouncing neutrons: quantum states

Neutrons with energy < 100 neV can bounce above a glass mirror.

The vertical motion is a simple quantum well problem

$$\frac{\hbar^2}{2m} \frac{d^2\psi}{dz^2} + mgz \psi = E \psi$$
Discovery of the quantum levels for the neutron bouncer


Neutron absorber

Mirror (glass),
Length 10 cm

\[
\begin{align*}
\bar{z}_1^{\text{exp}} &= 12.2 \pm 1.8_{\text{sys}} \pm 0.7_{\text{stat}} \ \mu m \\
\bar{z}_1^{\text{q.c.}} &= \frac{3}{2} \langle 1 | z | 1 \rangle = 13.7 \ \mu m
\end{align*}
\]
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Neutron inelastic reactions

- **Neutron capture**
  \[ n + {}^{A}X \rightarrow {}^{A+1}X^* + \gamma \quad \text{a. k. a. } X(n, \gamma) \]

- **Charged reactions**
  \[ n + {}^{A}X \rightarrow p + {}^{A}Y \quad \text{a. k. a. } X(n,p)Y \]
  \[ n + {}^{A}X \rightarrow \alpha + {}^{A-3}Z \quad \text{a. k. a. } X(n,\alpha)Z \]

- **Fission**
  \[ n + {}^{235}U \rightarrow PF_1 + PF_2 + \nu n \quad \text{a. k. a. } U(n,f) \]

**THE 1/\nu LAW**

\[ \sigma(\nu) = \sigma(\nu_0) \frac{\nu_0}{\nu} \]

One finds in tabulated neutron data the thermal cross sections

\[ \sigma^{th} = \sigma(2200 \text{ m/s}) \]
(n,p) reaction

Energy release
\[ Q = (m_X + m_n - m_p - m_Y) c^2 \]

Coulomb barrier
\[ B_c = \alpha \frac{\hbar c}{R_0} \frac{Z - 1}{1 + A^{1/3}} \]

Slow neutrons undergo (n,p) reaction only if
\[ Q > B_c \]

Only one possibility
\[ n + {^3}\text{He} \to p + t \]
(n,α) reaction

\[ n + \frac{A}{Z}X \rightarrow \alpha + \frac{A-3}{Z-2}Z \]

Energy release

\[ Q = (m_X + m_n - m_\alpha - m_Z)c^2 \]

Coulomb barrier

\[ B_c = \alpha \frac{\hbar c}{R_0} \frac{2 (Z - 2)}{4^{1/3} + (A - 3)^{1/3}} \]

Slow neutrons undergo (n,α) reaction only if

\[ Q > B_c \]

Only two possibilities

\[ n + ^6\text{Li} \rightarrow \alpha + t \]
\[ n + ^{10}\text{B} \rightarrow \alpha + ^7\text{Li} \]
Three neutron convertors

<table>
<thead>
<tr>
<th></th>
<th>$^3\text{He}(n, p)$</th>
<th>$^6\text{Li}(n, \alpha)$</th>
<th>$^{10}\text{B}(n, \alpha)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abundance</td>
<td>0.014 %</td>
<td>7.6 %</td>
<td>19.9 %</td>
</tr>
<tr>
<td>$\sigma^{\text{th}}$</td>
<td>5330 barn</td>
<td>937 barn</td>
<td>3837 barn</td>
</tr>
<tr>
<td>Kinetic energy of products</td>
<td>$p : 0.57 \text{ MeV}$</td>
<td>$\alpha : 2.05 \text{ MeV}$</td>
<td>$\alpha : 1.47 \text{ MeV}$</td>
</tr>
<tr>
<td></td>
<td>$t : 0.19 \text{ MeV}$</td>
<td>$t : 2.73 \text{ MeV}$</td>
<td>$\text{Li} : 0.84 \text{ MeV}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\gamma : 0.48 \text{ MeV}$</td>
</tr>
</tbody>
</table>

Gaseous detectors:
- proportional counters filled with $^3\text{He}$ or $\text{BF}_3$

Solid detectors:
- scintillators $\text{LiF}$
- silicon detectors with Boron solid conversion layer
(n,γ) capture

Energy release

\[ Q = (m_X + m_n - m_W)c^2 \]

a.k.a. the neutron separation energy of the nucleus W.

All stable nuclei have Q>0 EXCEPT for \(^4\)He.

Thus, \(^4\)He is the only stable element with zero capture cross section.
Validity of the $1/v$ law

\[ \sigma(v) = \sigma(v_0) \frac{v_0}{v} \]
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Big Neutron Sources

**FISSION**
- steady chain reaction
- ~ 2 neutron/fission
- Energy ~ 2 MeV

**SPALLATION**
- Accelerator driven
- Pulsed or steady
- ~ 20 neutrons/proton
- Energy ~ 20 MeV
Compare the neutron flux

PWR power reactor
Thermal neutron flux
~ $10^{14}$ n/cm$^2$/s

ILL high flux reactor
Thermal neutron flux
~ $1.5 \times 10^{15}$ n/cm$^2$/s

SNS pulsed source
Thermal neutron flux
Peak ~ $3 \times 10^{16}$ n/cm$^2$/s
Average ~ $4 \times 10^{13}$ n/cm$^2$/s
About 20 Big Neutron Sources worldwide

High flux reactors with cold neutron source available for users (there are 246 operational research reactors worldwide)

<table>
<thead>
<tr>
<th>Reactor</th>
<th>City</th>
<th>Country</th>
<th>Th. Power</th>
<th>Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILL</td>
<td>Grenoble</td>
<td>France</td>
<td>58 MW</td>
<td>46</td>
</tr>
<tr>
<td>HFIR</td>
<td>Oak Ridge</td>
<td>USA</td>
<td>85 MW</td>
<td>12</td>
</tr>
<tr>
<td>CARR</td>
<td>Beijing</td>
<td>China</td>
<td>60 MW</td>
<td>12</td>
</tr>
<tr>
<td>FRM II</td>
<td>Munich</td>
<td>Germany</td>
<td>20 MW</td>
<td>19</td>
</tr>
<tr>
<td>HANARO</td>
<td>Daejon</td>
<td>Korea</td>
<td>30 MW</td>
<td>8</td>
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<tr>
<td>WWR-M</td>
<td>Gatchina</td>
<td>Russia</td>
<td>18 MW</td>
<td>19</td>
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<tr>
<td>NIST</td>
<td>Gaithersburg</td>
<td>USA</td>
<td>20 MW</td>
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<tr>
<td>JRR-3M</td>
<td>Tokai</td>
<td>Japan</td>
<td>20 MW</td>
<td>26</td>
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<tr>
<td>BRR</td>
<td>Budapest</td>
<td>Hungary</td>
<td>10 MW</td>
<td>11</td>
</tr>
<tr>
<td>OPAL</td>
<td>Sydney</td>
<td>Australia</td>
<td>20 MW</td>
<td>7</td>
</tr>
<tr>
<td>BER II</td>
<td>Berlin</td>
<td>Germany</td>
<td>10 MW</td>
<td>22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spall. Source</th>
<th>City</th>
<th>Country</th>
<th>Beam Power</th>
<th>Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINQ @PSI</td>
<td>Villigen</td>
<td>Switzerland</td>
<td>1.5 MW</td>
<td>20</td>
</tr>
<tr>
<td>SNS @ORNL</td>
<td>Oak Ridge</td>
<td>USA</td>
<td>1.4 MW</td>
<td>25</td>
</tr>
<tr>
<td>JSNS @KEK</td>
<td>Tsukuba</td>
<td>Japan</td>
<td>0.3 MW</td>
<td>17</td>
</tr>
<tr>
<td>ISIS @RAL</td>
<td>Oxford</td>
<td>UK</td>
<td>0.2 MW</td>
<td>36</td>
</tr>
<tr>
<td>Lujan @LANSCE</td>
<td>Los Alamos</td>
<td>USA</td>
<td>0.1 MW</td>
<td>13</td>
</tr>
</tbody>
</table>

High intensity spallation sources available for users
ILL instrument suite
The ILL reactor

58 MW
Heavy water moderator and reflector
Fuel:
HEU (93.3% \(^{235}\)U)
Cold source
20 L of Liquid D\(_2\) at 20K
The ILL reactor
Source UCN PF2@ILL, since 1985

30 UCN / cm$^3$
Superthermal production of UCNs in superfluid 4He

Input: intense beam of cold neutrons with a wavelength of 8.9 Å

The superfluid Helium needs to be cooled down to 0.7 K
UCN sources in Europe

ILL 58 MW high flux reactor
- PF2 instrument, since 1985
UCNs extracted from 20K moderator
2 UCN/cm³ in EDM experiment
- Superfluid He source for GRANIT
first UCN in 2010,
now 4/cm³, 100/cm³ possible

Paul Scherrer Institute, Zurich
- PSI 600 MeV, 2.5 mA proton beam
  - lead spallation target
  - solid deuterium UCN convertor
First UCN in 2010
Designed for 50/cm³ in EDM experiment
Now 2/cm³